Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

White Paper Working Group Report

Stuart Henderson
Fermilab

U.S. DEPARTMENT OF ENERGY

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The White Paper is Available

http://www.science.doe.gov/hep/files/pdfs/ADSWhitePaperFinal.pdf

Background and Motivation – My Perspective

- Motivation:
  - Office of Science "Energy Mission"
  - Increasing and expanding R&D efforts world-wide, including international interest in U.S. superconducting linac technology
  - Yucca mountain closure
- Questions:
  - Have there been fundamental developments in the underlying technology in the last 10-15 years that would change the practicality of accelerator-driven systems ?
  - Is the technology ready to support a demonstration program?

The White Paper

- A Working Group was tasked through DOE/OHEP with producing a White Paper on Accelerator and Target technology for Accelerator-Driven Systems (ADS)
- The White Paper was intended to address
  - the technical requirements for ADS
  - the current status of accelerator/target technology with respect to those requirements
  - the R&D necessary to meet the requirements
  - the readiness of technology for a demonstration program
- In addition, underlying questions that this white paper was intended to answer include:
  - Do the advances that have been made in Accelerator Technology in the last 10-15 years change the practicality of ADS for processing waste and generating electricity?
  - Is the technology to the point where a demonstration program is warranted?

Working Group Membership

- Hamid Aït Abderrahim, SCK-CEN
- John Galambos, ORNL
- Yousry Gohar, ANL
- Stuart Henderson*, FNAL
- George Lawrence, LANL, retired
- Tom McManamy, ORNL
- Alex Mueller, CNRS-IN2P3
- Sergei Nagaitsev, FNAL
- Jerry Nolen, ANL
- Eric Pitcher*, LANL
- Bob Rimmer, TJNAF
- Richard Sheffield, LANL
- Mike Todosow, BNL

*Co-chairs

Approach

- The White Paper focuses on **Accelerator and Target Technology** and its status relative to requirements for ADS
- We **intentionally avoided** the many important and related questions of economics of ADS, ADS vs. fast reactors, ADS fuel cycles, impact on long-term storage, separations technology, fuel forms, etc., etc.
- Our interaction with (some of) these issues enters only at the high-level requirements stage
- Goal was to produce a **hard-nosed assessment** of the technology, sticking to **verifiable facts**, and **avoiding salesmanship**
- It is expected that the next step would bring together experts in accelerator/target technology with those in subcritical reactors and fuel cycles

Applications of Accelerator Driven Systems Technology

- Accelerator Driven Systems may be employed to address several missions, including:
  - Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to reduce the burden these isotopes place on geologic repositories.
  - Generating electricity and/or process heat.
  - Producing fissile materials for subsequent use in critical or sub-critical systems by irradiating fertile elements.

Timeline of US ADS Activities

- Since the early 1990's, accelerator-driven systems have been proposed for addressing certain missions in advanced nuclear fuel cycles
- In 1995 the National Research Council issued a report on transmutation technologies ("The NRC Report") which included an evaluation of one ADS concept for a ~100 MW accelerator to drive a thermal, molten salt subcritical core
- The NRC recognized the many complexities associated with this system, among them that much of the required high-power accelerator technology had yet to be demonstrated
- The NRC report was quite negative on accelerator applications in fuel cycles

NRC Study (1996) Accelerator Parameters: Based on 1992 Normal-Conducting (coupled-cavity) Linac Design

	ATW-1	ATW-2	Present Day
Beam Energy [MeV]	1600	800	1500
Beam Power [MW]	400	88	75
Accelerating Gradient	1 MV/m	1 MV/m	20 MV/m
Linac Length	1900 m	1000m	300 m

Timeline of US ADS Activities

- 1999: US Congress directed DOE to evaluate Accelerator Transmutation of Waste (ATW) concepts and prepare a “roadmap” to develop the technology
- 2000-2002, DOE sponsored the Advanced Accelerator Applications to investigate use of ADS in closed fuel cycles
- 2003: AAA program transitioned to the Advanced Fuel Cycle Initiative and DOE sponsored ADS research ceased (except for continuation of a few international collaborative efforts)

World-wide ADS research activities

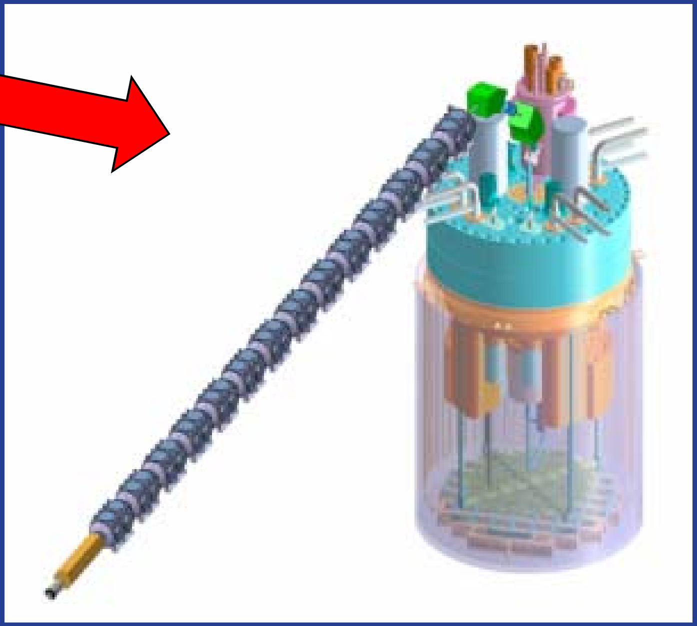
- Meanwhile, outside the US, ADS R&D for both transmutation and power generation has not only continued but accelerated
- 2001: European Technical Working Group evaluated the state of ADS technologies and recommended construction of an experimental ADS
- 2002: OECD/NEA convened an expert panel which produced a report, "Accelerator Driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles"; they concluded

  "On the whole, the development status of accelerators is well advanced, and beam powers of up to 10 MW for cyclotrons and 100 MW for linacs now appear to be feasible. However, further development is required with respect to the beam losses and especially the beam trips to avoid fast temperature and mechanical stress transients in the reactor."

Summary of World-wide ADS Activities

Europe- EUROTRANS program

- "R&D efforts aiming at substantiating the potential of ADS and studying their role in innovative reactor and fuel cycle strategies that include systems for large-scale utilization and transmutation of minor actinides and long-lived fission products"
- Technology demonstration is gaining momentum with Belgium's plans for MYRRHA, an 85-MW demonstration ADS at SCK●CEN
- Gov't has committed to funding 40% of the construction cost and is investing 60 MEuro over the next 5 years to advance the design in preparation for construction start in 2015



Summary of World-wide ADS Activities

Europe- Energy Amplifier

- CERN Group (C. Rubbia)
- ThorEA – Thorium Energy Amplifier Association, UK: "Capturing thorium-fueled ADSR energy technology for Britain"

India

- Envision synergistic role of ADS within the larger Indian nuclear power program for electricity production, fertile-fissile conversion of Th, nuclear waste incineration
- Objectives of ADS R&D programme
  - Partitioning & Transmutation as part of advanced fuel cycles
  - Fissile material breeding → thorium utilization

Summary of World-wide ADS Activities

Japan

- Japan Atomic Energy Agency (JAEA)
  - Sub-critical core design studies: 800 MWth Pb-Bi eutectic cooled ADS
  - TEF (Transmutation Experimental Facility) is being designed for deployment at J-PARC (Japan Proton Accelerator Research Complex)
- Experimental program on subcritical core-100 MeV proton beam coupling at Kyoto University

South Korea

- Studying ADS for transmutation of waste
- Design and construction of 1st stage of a high-power proton accelerator at KAERI (KOMAC)

Summary of World-wide ADS Activities

China, Ukraine, Russia, Belarus, Brazil

- Ongoing programs in accelerator-driven transmutation of waste and Th fuel utilization

There is no active U.S. Program in ADS technology

Finding #1

There are active programs in many countries, although not in the U.S., to develop, demonstrate and exploit accelerator-driven systems technology for nuclear waste transmutation and power generation.

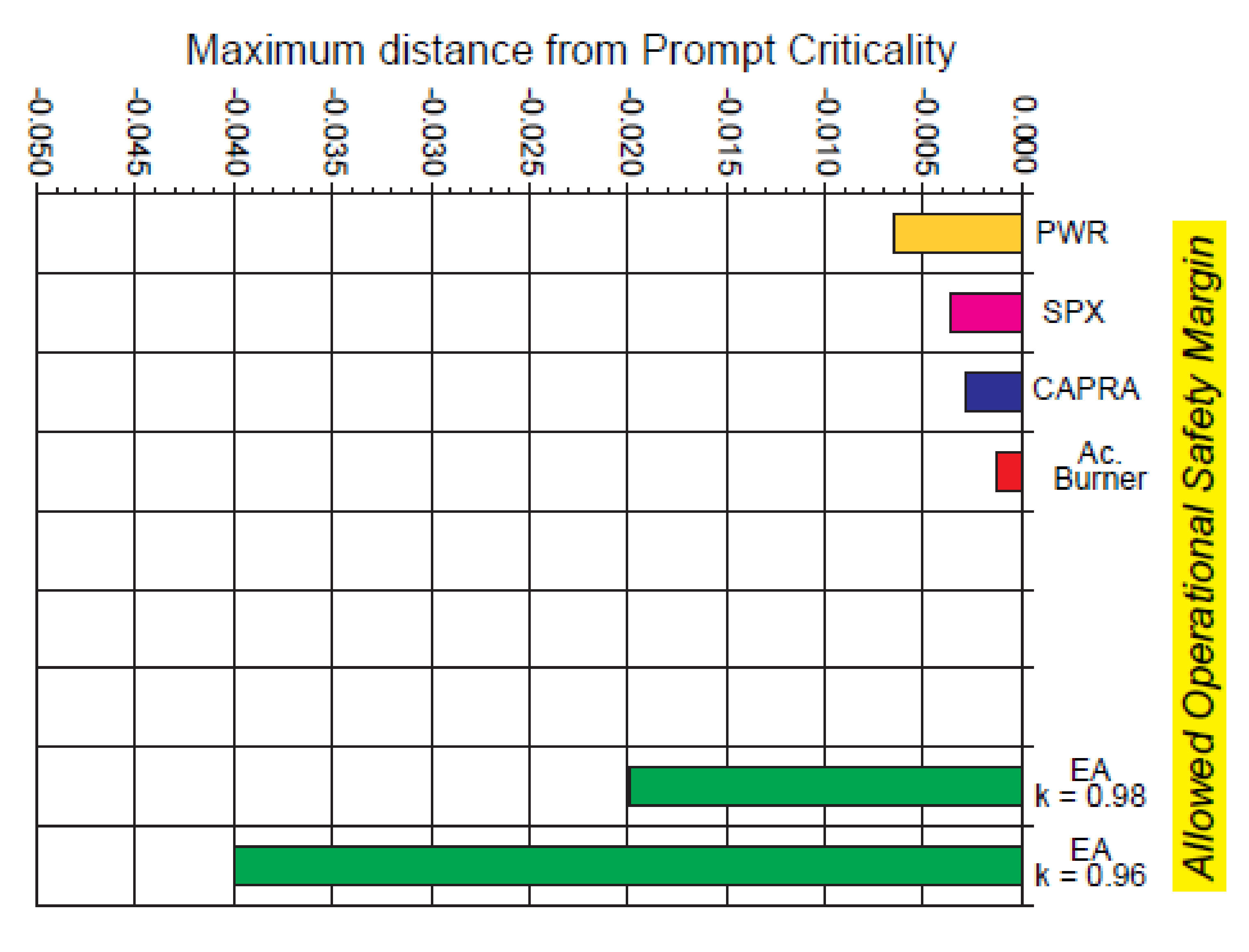
Why ADS?

- Comparisons of critical reactors and ADS have been carried out (see, e.g. OECD/NEA Report)
- Principal advantages of ADS are
  1. greater flexibility with respect to fuel composition, and
  2. potentially enhanced safety

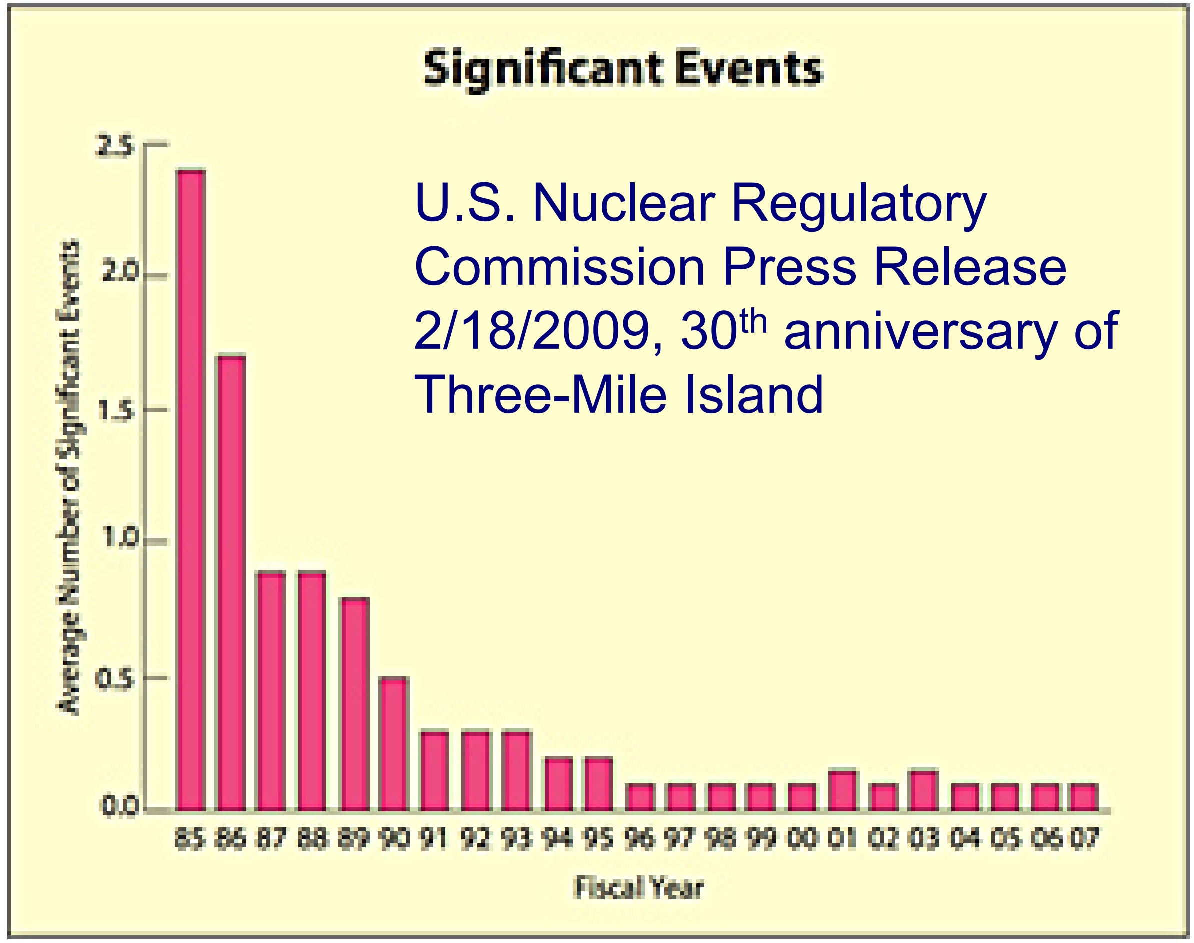
Fuel Flexibility

- Accelerator driven systems are ideally suited to burning fuels which are problematic from the standpoint of critical reactor operation, namely, fuels that would degrade neutronic characteristics of the critical core to unacceptable levels due to small delayed neutron fractions and short neutron lifetimes, such as minor actinide fuel.
- Additionally, ADS allows the use of non-fissile fuels (e.g. Th) without the incorporation of U or Pu into fresh fuel.

Margin to Prompt Criticality



(Stuart's) Thoughts on Safety

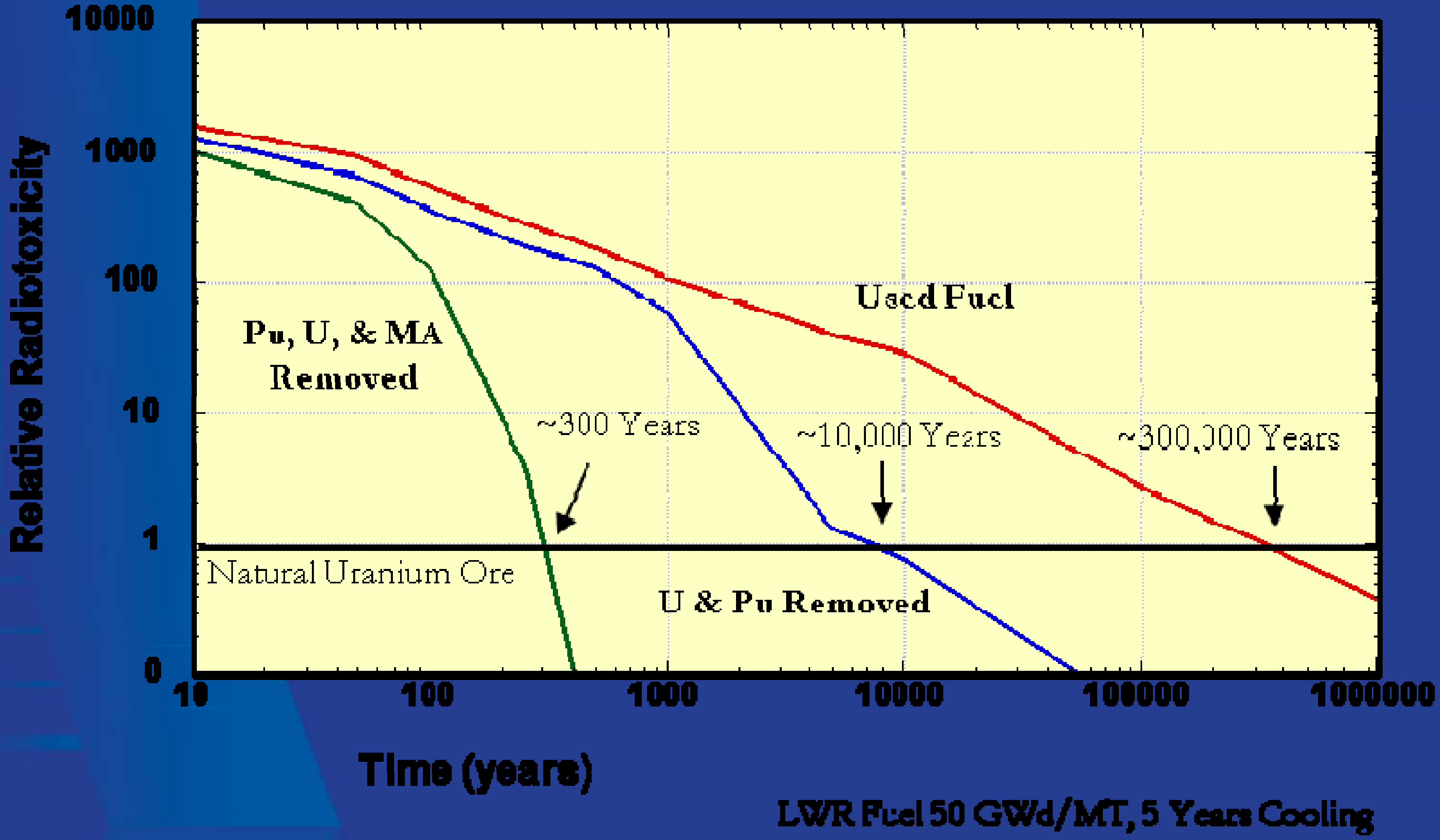


U.S. Nuclear Regulatory Commission Press Release 2/18/2009, 30th anniversary of Three-Mile Island

Finding #2

Accelerator-driven sub-critical systems offer the potential for safely burning fuels which are difficult to incorporate in critical systems, for example fuel without uranium or thorium.

Transmutation of Waste

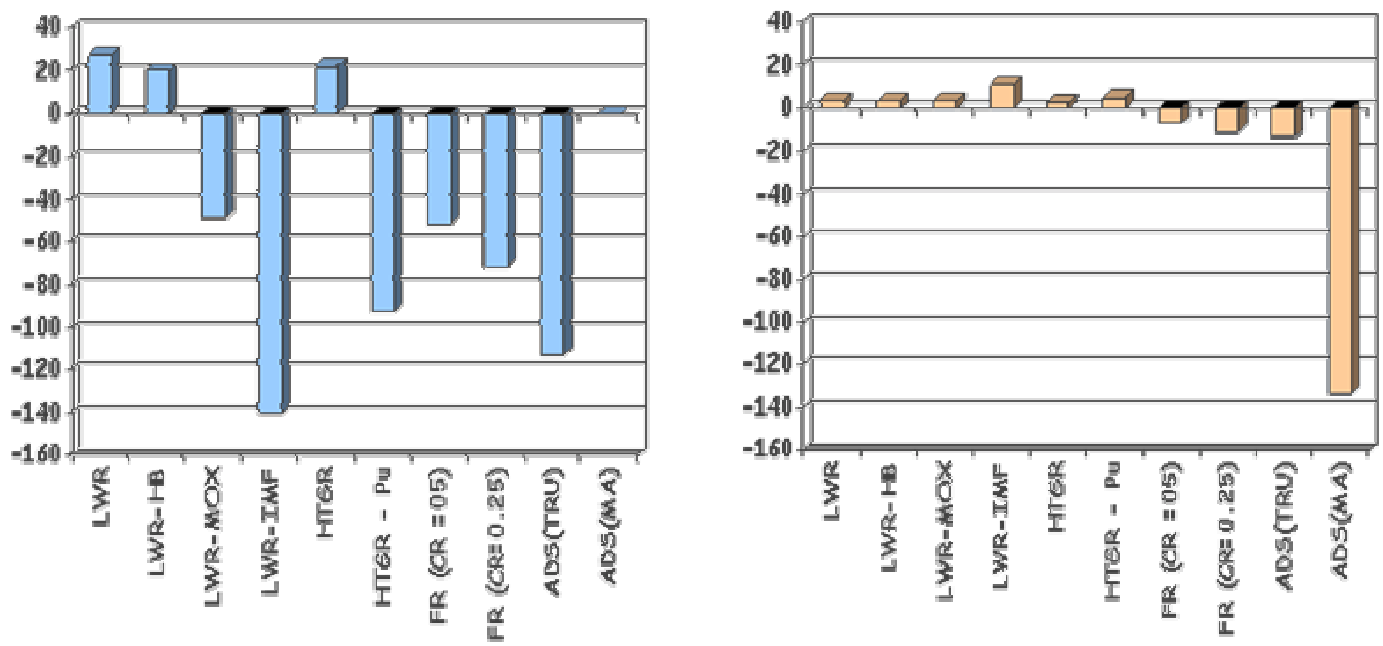


ADS for Waste Transmutation

- Minor actinide destruction through transmutation is one mission that ADS are well suited to address.
- Unlike critical fast reactors which generally incorporate uranium or thorium in the fuel for safe operation, ADS can potentially operate on a pure MA feed stream, meaning a smaller number of ADS can be deployed to burn a fixed amount of minor actinides.
- ADS can recycle the MA multiple times until it is completely fissioned, such that the only actinide waste stream from these systems would derive from the recycling residuals, which could yield a significant reduction (by a factor of hundreds) in the amount of actinide waste per kW-hr of electricity generated, as compared to a once-through fuel cycle.
- Because accelerator driven systems do not require fuels containing uranium or thorium, they are more efficient at destroying MA waste

M. Cappiello, "The Potential Role of ADS in the U.S."

The ADS is most efficient at Minor Actinide Transmutation



Pu Production Rate (grams / GWh) **MA Production Rate (grams / GWh)**

Finding #3

Accelerator driven subcritical systems can be utilized to efficiently burn minor actinide waste.

Power Production

- A facility for transmutation of waste would also generate substantial power; the process heat could be utilized to produce another form of energy (e.g. biofuels) or could be used to generate electrical power.
- Many proposed ADS concepts with the goal of power production utilize thorium-based fuel to take advantage of some of its benefits, including greater natural abundance, proliferation resistance, and significantly reduced production of transuranics which are a major source of radiotoxicity and decay heat relative to uranium-based fuel.
- An ADS system based on Th fuel would not require incorporation of fissile material into fresh fuel, and could operate almost indefinitely in a closed fuel cycle.
- Expanded use of thorium-based fuels is actively pursued in some countries with large reserves of thorium, principally India, Norway and China. These programs are investigating whether ADS can speed up the deployment of the ^{233}U-Th fuel cycle by breeding ^{233}U, which does not exist in nature.

Finding #4

Accelerator driven subcritical systems can be utilized to generate power from thorium-based fuels

Range of Missions for Accelerator Driven Systems

Transmutation Demonstration and Experimentation →	Industrial-Scale Transmutation →	Industrial-Scale Power Generation w/ Energy Storage →	Industrial-Scale Power Generation w/o Energy Storage
• Accelerator sub-critical reactor coupling • ADS technology and components • M.A./Th fuel studies	• Transmutation of M.A. or Am fuel • Convert process heat to another form of energy	• Deliver power to the grid • Burn MA (or Th) fuel • Incorporate energy storage to mitigate long interruptions	• Deliver power to the grid • Burn MA (or Th) fuel

→ Time, Beam-Trip Requirements, Accelerator Complexity, Cost

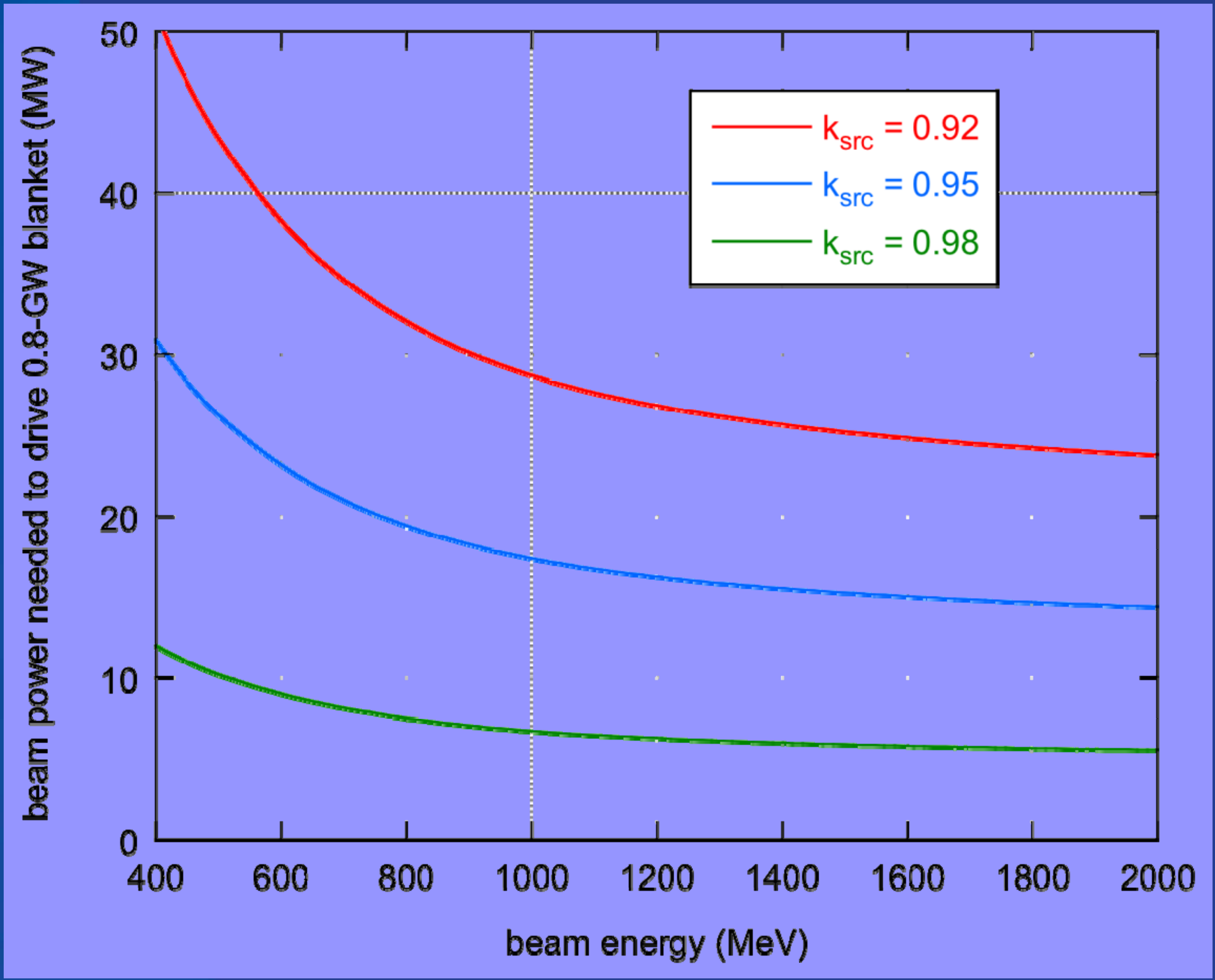
Finding #5

The missions for ADS technology lend themselves to a technology development, demonstration and deployment strategy in which successively complex missions build upon technical developments of the preceding mission.

ADS System Level Requirements

- Beam Energy: GeV range
- Beam Power: ~1 MW for demonstration up to many tens of MW for an industrial scale system
- Beam Time Structure: continuous
- Beam Trip Frequency
- System Availability: low for demonstration, high for a commercial system

Beam Power Requirements



Reliability

- More than any other requirement, the maximum allowable beam trip frequency has been the most problematic, and in many ways has been perceived as a “show-stopper”
- Conventional wisdom held that beam trips had to be limited to a few per year to avoid thermal stress and fatigue on the reactor structures, the target and fuel elements

Beam Trip Requirements in ATW-related studies ca. 2002

LA-UR-02-6684
Approved for public release; distribution is unlimited.

Title: **Reliable-Linac Design for Accelerator-Driven Subcritical Reactor Systems**

Author(s): Thomas P. Wangler

Proc. of the 3rd Workshop on Utilization and Reliability of High Power Proton Accelerators, Santa Fe, USA, 12-16 May 2002, p. 49.

Table II. Beam Requirements for an ATW

PARAMETER	REQUIREMENT
Energy (GeV)	0.6 – 1.5
Current (mA)	10 - 100
Beam Power (MW)	10 - 100
Linac Beam Loss (W/m)	< 1 W/m required and < 0.1 W/m goal
Beam Interrupts > ~1 s	<100/year≈0.01/hr
Beam Interrupts > ~10 min	<2/year≈0.0002/hr

Beam Trip Requirements in EUROTRANS Studies

Eur. Phys. J. Special Topics **176**, 179–191 (2009)

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THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

Regular Article

Prospects for transmutation of nuclear waste and associated proton-accelerator technology

A.C. Mueller

National Institute for Nuclear and Particle Physics, CNRS, 75016 Paris, France

Table 4. Main specifications for the proton beam. The listed requirements are for driving the technology-demonstrator XT-ADS compared to the industrial prototype EFIT.

	XT-ADS	EFIT
Max. beam intensity	2.5–4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertical from above	
Allowed beam trips (>1 sec)	<5 per 3-month operation cycle	<3 per year
Beam stability	Energy: ±1%, Intensity: ±2%, Size: ±10%	
Beam time structure	CW, including zero-current periods (200 μs), repeated at low rate	

Recent Beam Trip Duration Analyses

- There are three analyses based on transient response of reactor components using modern FEA methods: JAEA, MYRRHA and Argonne
- These analyses show relatively good agreement

JAEA Analysis: H. Takei et. al., Proc. 5th OECD/NEA HPPA

Four criteria depending on the beam trip duration *T*

Beam trip duration *T*	Acceptable Frequency	Remarks
$0 < T < 5$ sec.	10^5 / 2 year 10^6 / 40 year (25,000 / y)	Beam window life time Fatigue failure of reactor structure
$5 < T < 10$ sec.	10^5 / 40 year (2,500 / y)	Fatigue failure of reactor structure
10 sec. $< T <$ 5 min.	10^4 / 40 year (250 /y)	Fatigue failure of reactor structure
$T >$ 5 min.	Once a week (50 /y)	System availability

Beam Trip Requirements

- Understanding of allowable beam trip-rates has improved greatly, resulting in ~2 order of magnitude relaxation of requirements for “short” trips and ~1 order of magnitude relaxation for “long” trips
- Updated Beam-Trip Rate requirements, while still very challenging, appear manageable with i) modern linac architecture, ii) appropriate redundancy and iii) utilization of reliability engineering principles
- More work is required to bring these components together with high reliability at > 10 times the beam power of today’s accelerators, but “getting from here to there” is achievable

Finding #6

Recent detailed analyses of thermal transients in the subcritical core lead to beam trip requirements that are much less stringent than previously thought; while allowed trip rates for commercial power production remain at a few long interruptions per year, relevant permissible trip rates for the transmutation mission lie in the range of many thousands of trips per year with duration greater than one second.

Range of Parameters for ADS

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

ADS-Relevant Technology Development in the Last 10-15 Years

- Modern, MW-class high power proton accelerators exist (Spallation Neutron Source)
- Key technologies have been demonstrated
  - High-power Injector technology has been built and *demonstrated ADS-level performance (100 MW equivalent) with beam* (Low-Energy Demonstration Accelerator at Los Alamos)
  - Superconducting radiofrequency structures have been built which cover a broad range of particle velocities (from v/c=0.04 to 1). Use of SRF offers potential for achieving high reliability
  - Liquid-metal target systems have operated with MW proton beams (Pb-Bi loop - MegaPIE @ PSI, liquid Hg @ SNS)
- **Key technologies of relevance for ADS applications that existed only on paper ~15 years ago have since been developed and demonstrated**

Accelerator Technology - Requirements

	Transmutation Demonstration (MYRRHA [5])	Industrial Scale Facility driving single subcritical core (EFIT [10])	Industrial Scale Facility driving multiple subcritical cores (ATW [11])
Beam Energy [GeV]	0.6	0.8	1.0
Beam Power [MW]	1.5	16	45
Beam current [mA]	2.5	20	45
Uncontrolled Beamloss	< 1 W/m	< 1 W/m	< 1 W/m
Fractional beamloss at full energy (ppm/m)	< 0.7	< 0.06	< 0.02

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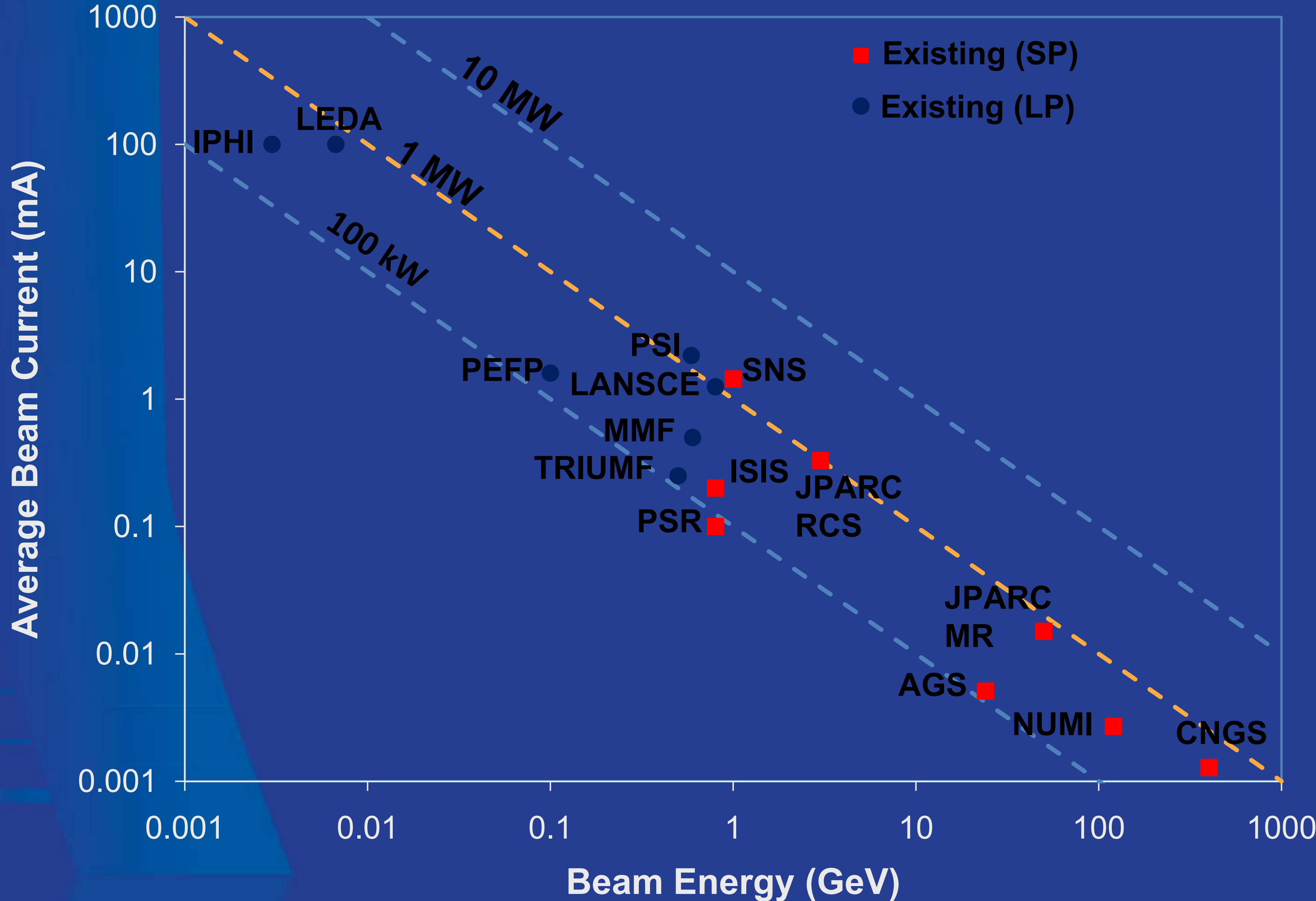
The Beam Power Landscape



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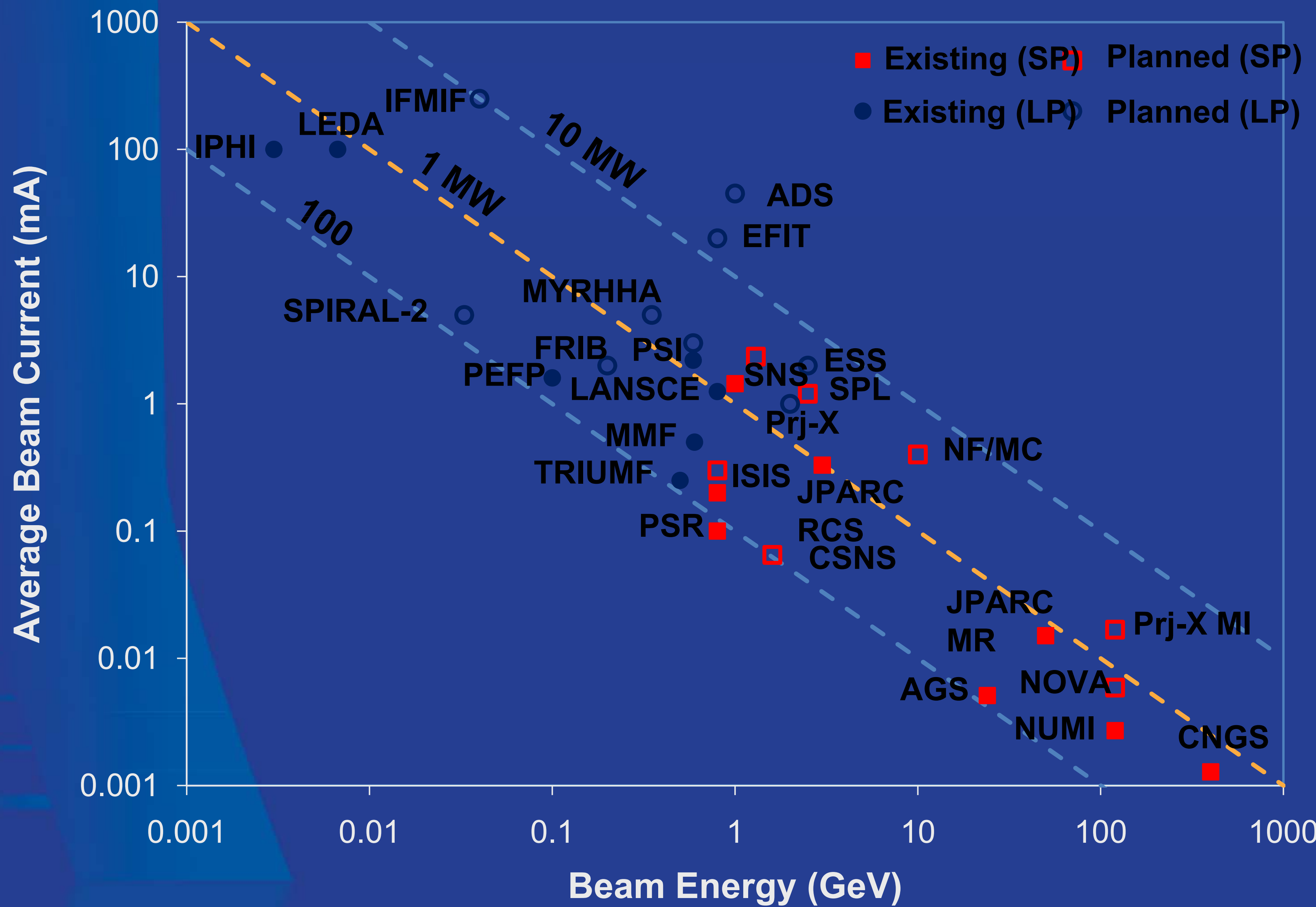
The Beam Power Landscape



Accelerator Technology Choices

- Three technologies have demonstrated MW-level performance
  - Cyclotron – PSI
  - NC Linac – LANSCE
  - SC Linac – SNS
- Alternative approaches to high power include
  - Synchrotron technology
  - Fixed-field alternating gradient (FFAG) technology
  - Combining multiple beams (stacked cyclotron approach – P. McIntyre et. al.)

Accelerator Technology Choices, cont'd

- In the range of 5-10 MW, both cyclotron (at its limits) and linear accelerator technology are applicable. Perhaps FFAGs will be capable someday.
- For beam power in excess of ~10 MW, only SC RF linac technology appears to be practical
- Various studies have concluded that SC RF technology has far greater beam power potential than cyclotron technology, and that it is the technology of choice for the > 10MW beam power required to drive GW-level subcritical cores
- Further, SCRF has the capability for achieving very high reliability as it lends itself to implementing a robust independently-phased radio-frequency cavity system. It is that latter technology that has the potential for fault tolerance and rapid fault recovery, making use of built-in online spare cavities.

Finding #7

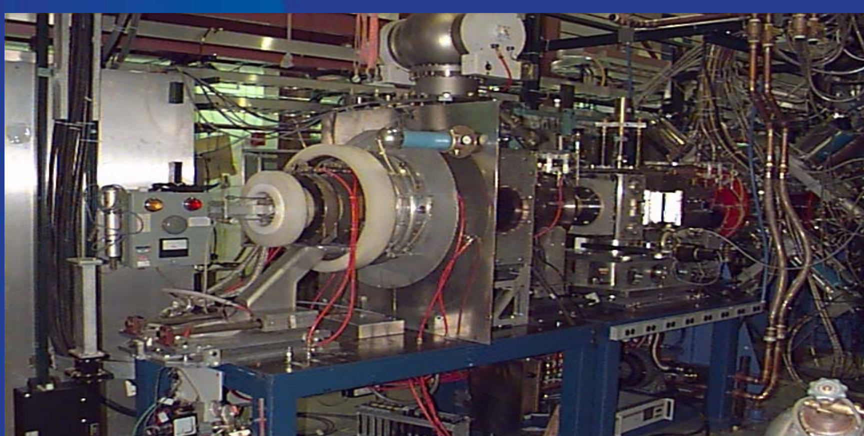
For the tens of MW beam power required for most industrial-scale ADS concepts, superconducting linear accelerator technology has the greatest potential to deliver the required performance.

State of the Art in Accelerator Technology

- Front-end Injector Systems
- Superconducting RF Acceleration Systems
- Beam Dynamics and Beam Loss
- Reliability and Beam Trip Rate

Front-End System Technology: Low-Energy Demonstration Accelerator (LEDA)

- Full power performance demonstrated for a limited operating period.
  - 20 hours at 100 mA CW
  - 110 hours at > 90 mA CW
- RMS beam emittances measured; reasonable agreement with simulation
- No long-term operations for reliability/availability evaluation.
- HPRF system performed well, but no long-term window tests.



SILHI: Source of Light Ions for High Intensity at CEA-Saclay

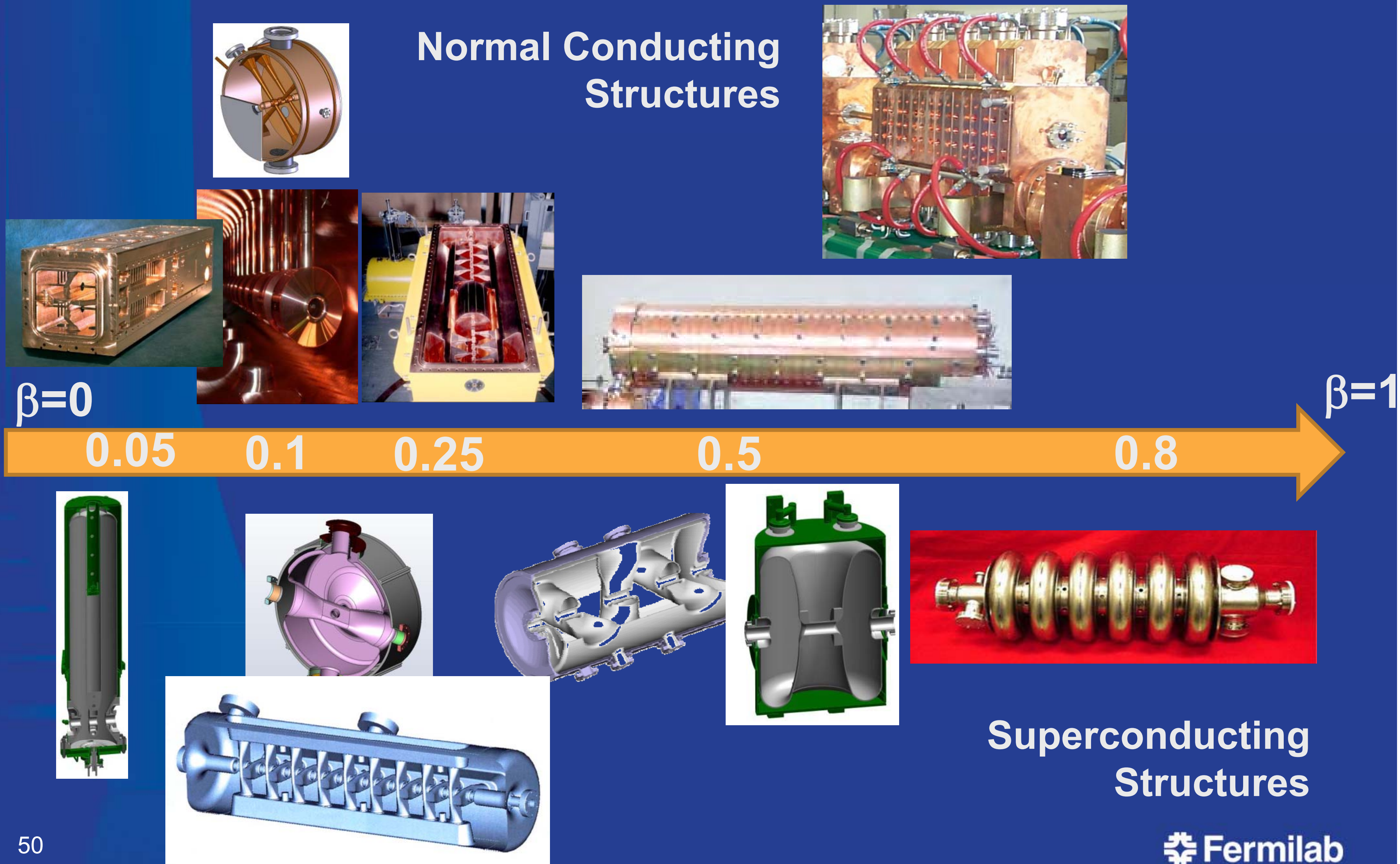
- An ECR-based injector (SILHI) was built and tested, extracting > 100 mA.
- The source was operated for ~1,000 hours to assess reliability and availability;

Parameters	Déc. 97	Mai 99	Oct. 99	March 01	June 01
Energy (keV)	80	95	95	95	95
Intensity (mA)	100	75	75	118	114
Duration (h)	103	106	104	336	162
Beam off number	**53**	**24**	**1**	**53**	**7**
MTBF (h)	**1.75**	**4**	**n. appl.**	**≈ 6**	**23.1**
MTTR (mn)	**6**	**5.3**	**2.5**	**≈ 18**	**2.5**
Uninterrupted beam (h)	**17**	**27.5**	**103**	**25**	**36**
Availability (%)	**94.5**	**97.9**	**99.96**	**95.2**	**99.8**

Finding #8

One of the most challenging technical aspects of any ADS accelerator system, the Front-End Injector, has demonstrated performance levels that meet the requirements for industrial-scale systems, although reliability at these levels has not yet been proven.

A Zoo of RF Structures for β < 1 Acceleration

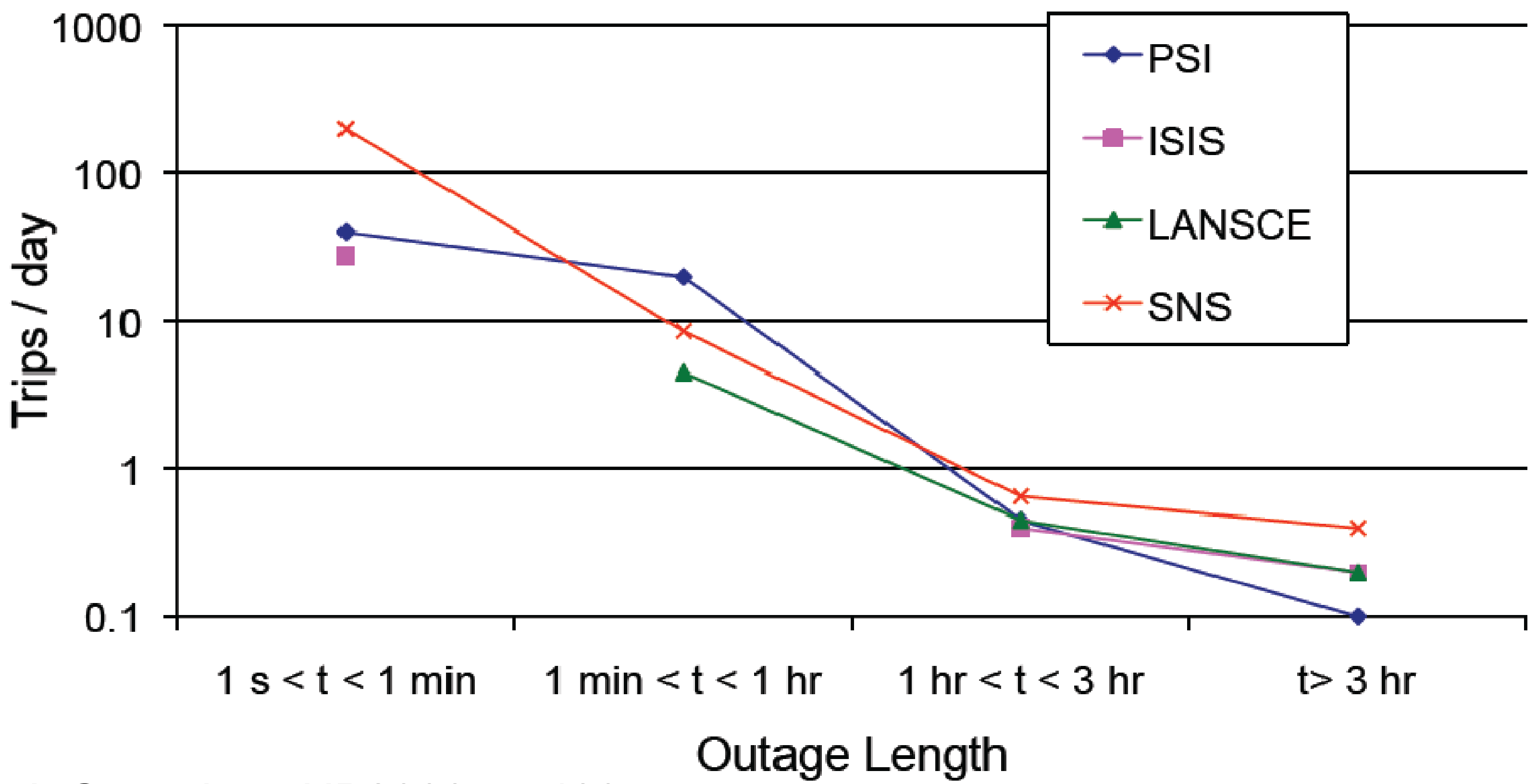


Finding #9

Superconducting radio-frequency accelerating structures appropriate for the acceleration of tens of MW of beam power have been designed, built and tested; some structure types are in routinely operating accelerator facilities.

Beam Trip Duration Experience

- It is instructive to look at the experience, but one must keep in mind that operating proton accelerators were not designed for low trip rates



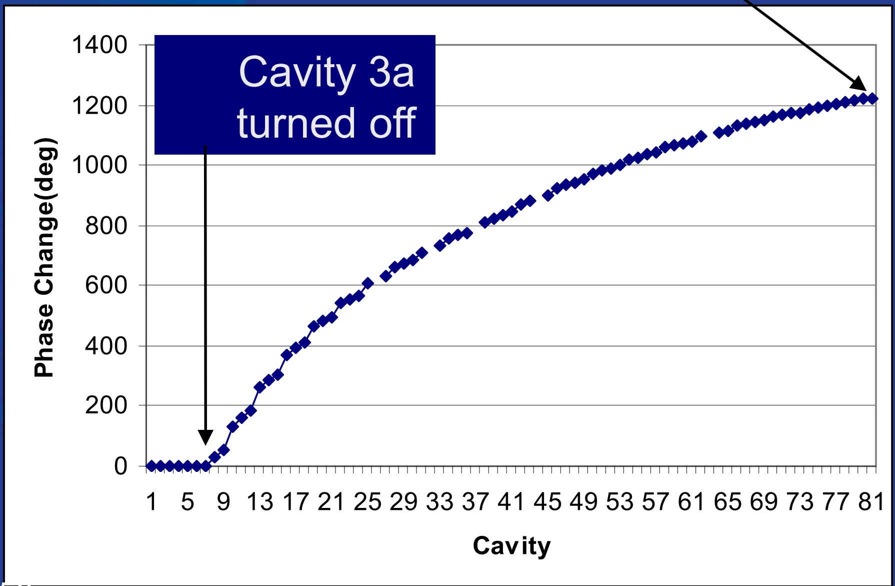
J. Galambos, HB2008, p. 489

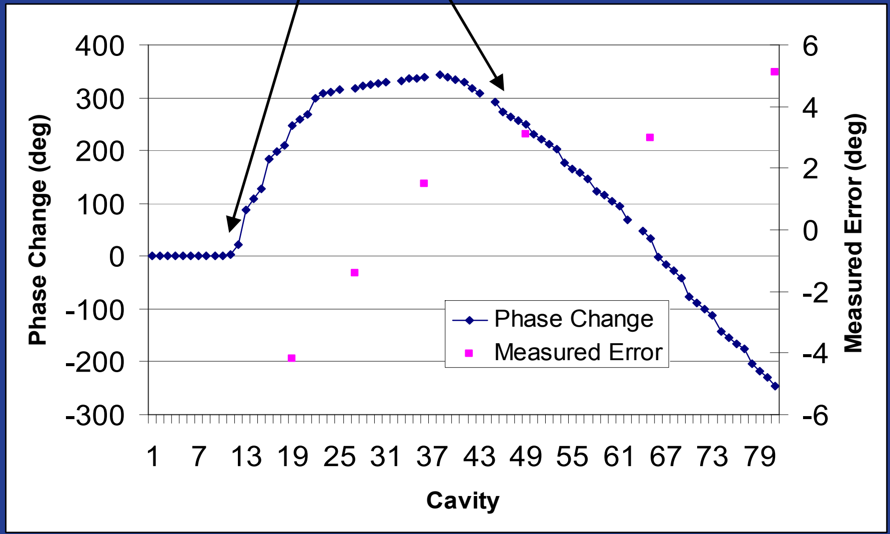
Superconducting Cavity Fault Recovery

- A cavity fault recovery scheme is developed to adjust downstream cavity setup, to accommodate upstream cavity changes
  - Uses a difference technique, with initial beam based measurements
  - Successfully demonstrated and used at SNS
    - Could work in < 1 sec if needed

Final cavity phase found within 1 degree, output energy within 1 MeV

Turned on cavity 4a, reduced fields in 11 downstream cavities





Courtesy J. Galambos

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Finding #10

Ten to one-hundred fold improvement in long-duration beam trip rates relative to those achieved in routine operation of existing high power proton accelerators is necessary to meet industrial-scale ADS application requirements.

Finding #11

The technology available to accelerator designers and builders of today is substantially different from, and superior to, that which was utilized in early ADS studies, in particular in the design which was considered in the 1996 National Research Council report.

Accelerator Technology R&D Priorities

Front-end Systems

- Demonstrated long-term operation at high CW power levels, with assessment of reliability and availability
- Construction and long-term operation of an ADS plant-level accelerator front end, including the low-velocity section
- Confirmation of matching, beam quality and minimal halo growth
- Exploration of beam scraping schemes
- Demonstration of fast beam switching capability from a hot-spare front-end

Superconducting radiofrequency cavity technology

- Demonstration, with beam, of robust SRF cavity designs for all beta values
- Experimental verification of fast trip recovery techniques
- Robust coupler and fast tuner technology
- Reliable low-cost RF sources
- Improved cleaning and processing techniques for low-frequency elliptical and spoke cavities are needed

Accelerator Technology R&D Priorities

Beam dynamics

- Modeling of beam loss and halo mechanisms
- Benchmarking of beam loss and halo models with actual accelerator performance
- SC linac lattice design for maximum fault tolerance

Beam instrumentation

- High dynamic range, high-resolution measurement of beam particle distributions.
- High dynamic range, high-resolution measurement of beam phase-space distributions throughout the entire energy range

Reliability

- Analysis of beam trip data in existing prototypical accelerators
- Development and deployment of rapid fault-recovery schemes in SRF linacs

Target Systems- Requirements

- Maximize the number of neutrons *escaping* from the target per proton incident on it.
- Accommodate high deposited power density (~1 MW/liter).
- Relative to the subcritical core, contribute in an insignificant way to the dose received by workers and the public under design basis accident scenarios.
- Operate reliably for more than six months between target replacements.
- Be capable of being replaced within a reasonable (about one week) maintenance period.

Target Systems – Technology Choices

- Solid target options, which consist of a solid material in the form of rods, spheres, or plates to produce the neutrons, and coolant flowing between the elements for heat removal.
- Liquid target options where a flowing liquid metal (LM) acts both as the source of neutrons and the heat removal media.

Target Technology Design Issues

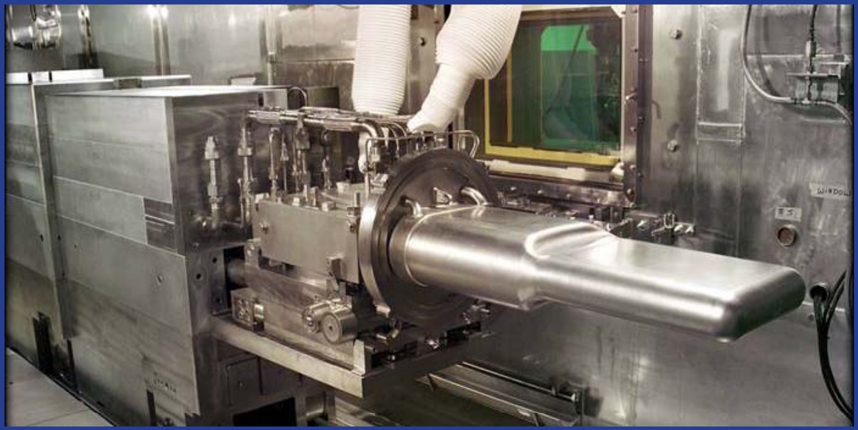
- Neutronics
  - Maximizing the neutrons/proton emerging from the target
  - trade-offs between engineering, materials, safety, operational, and cost considerations.
- Thermal Hydraulics
  - Heat Removal from target and window
  - Design considerations include material compatibility, safety, radiation damage, remote handling and required reliability.
- Safety
  - Adequate cooling
  - Maintaining structural integrity
  - Manage/contain radioactive inventory
  - Accommodate accelerator induced transients

Target Technology Design Issues, cont'd

- Target Lifetime
  - Limitations from radiation-induced degradation of mechanical properties
  - Corrosion and erosion from coolant (oxygen control in LBE to avoid corrosion)
- Accelerator/Target Interface
  - Beam profile control and measurement
  - Equipment protection for off-normal events
- Maintenance and Remote Handling

State of the Art: Operating MW-class Target Systems

- Solid-target
  - SINQ at PSI (~1.2 MW "DC" beam)
- Liquid Hg
  - Spallation Neutron Source (1.1 MW pulsed)
  - Japan Proton Accelerator Research Complex (0.3 MW pulsed)
- Pb-Bi Eutectic target
  - MEGAPIE at PSI (0.8 MW)
- Spallation targets for ADS application well above 1 MW will likely use heavy liquid metal cooling to achieve compact designs.
  - The only example of lead or LBE cooling for high power is the Russian LBE submarine reactors which were designed for approximately 150 MW.



Finding #12

Spallation target technology has been demonstrated at the 1-MW level, sufficient to meet the "Transmutation Demonstration" mission.

R&D Needs for Target Technology

Liquid Metal Targets

- Oxygen control in an LBE environment. A number of out-of-beam LBE loops with oxygen control exist today that can be used to further develop appropriate operating conditions that limit corrosion of steels in contact with LBE. This testing should be augmented by one or more long-term in-beam tests.
- Polonium release from LBE. To support safety analyses, measure Po release fractions from LBE as a function of LBE temperature and concentration of trace contaminants.
- LBE cleanup chemistry. To limit corrosion of steels in contact with LBE, develop LBE cleanup chemistry techniques.
- Plate out of spallation products throughout the circulating LM system (piping, heat exchanger(s), filters) is likely with an LM target. The impact on personnel dose and ways to ensure RAMI (Reliability, Availability, Maintainability and Inspectability) and ways to mitigate adverse consequences should be explored.
- Develop criteria, verified by testing, required for safe and reliable operation of a windowless (LBE) liquid target.

R&D Needs for Target Technology

Solid Targets

- While LM targets have several benefits in high power density compact applications, the potential of solid targets to satisfy mission requirements should not be ignored. The principal benefit of a solid target is that the radioactive spallation products are generally confined to the solid target material and are localized in the target proper. The radioactivity in the primary coolant will depend on the coolant utilized and the design of the primary coolant loop, but should be significantly less of an issue than for LM targets.
- Solid target options should be evaluated and their performance and ES&H characteristics compared to those of LM targets. Carrying along a solid target option at the early stages of ADS conceptual design, if warranted by the comparative studies suggested above can reduce programmatic risk.

R&D Needs for Target Technology

Independent of Target Type (Liquid or Solid)

- Materials irradiations. Extend the irradiated materials database to include ADS environmental conditions (elevated temperature, contact with liquid metal, fatigue) and structural materials relevant to ADS applications.
- Subscale heat transfer and flow testing at operating temperatures.
- Full scale testing at operating temperatures.
- Off normal testing of safety systems
  - Leak containment – thermal shock on structures
  - Decay heat removal – natural convection testing may be needed
- Component testing under operating and off normal conditions.
- Remote handling development testing for components.
- Develop higher frequency (10-100 kHz), redundant/fail-safe raster power supplies and magnets with telescopic image magnification (2-4x) for uniform circular beam spots.
- Develop real-time, non-destructive beam imaging for 10-100 mA – e.g. residual gas fluorescence imaging.
- Develop through large-scale simulations detailed criteria for beam-trip recovery scenarios to minimize damage to liquid target and solid or liquid fuel containment vessels.
- Examine issues associated with integral cooling of the target and the sub-critical blanket via a single loop.
- Address interface issues of the target with the accelerator and sub-critical blanket

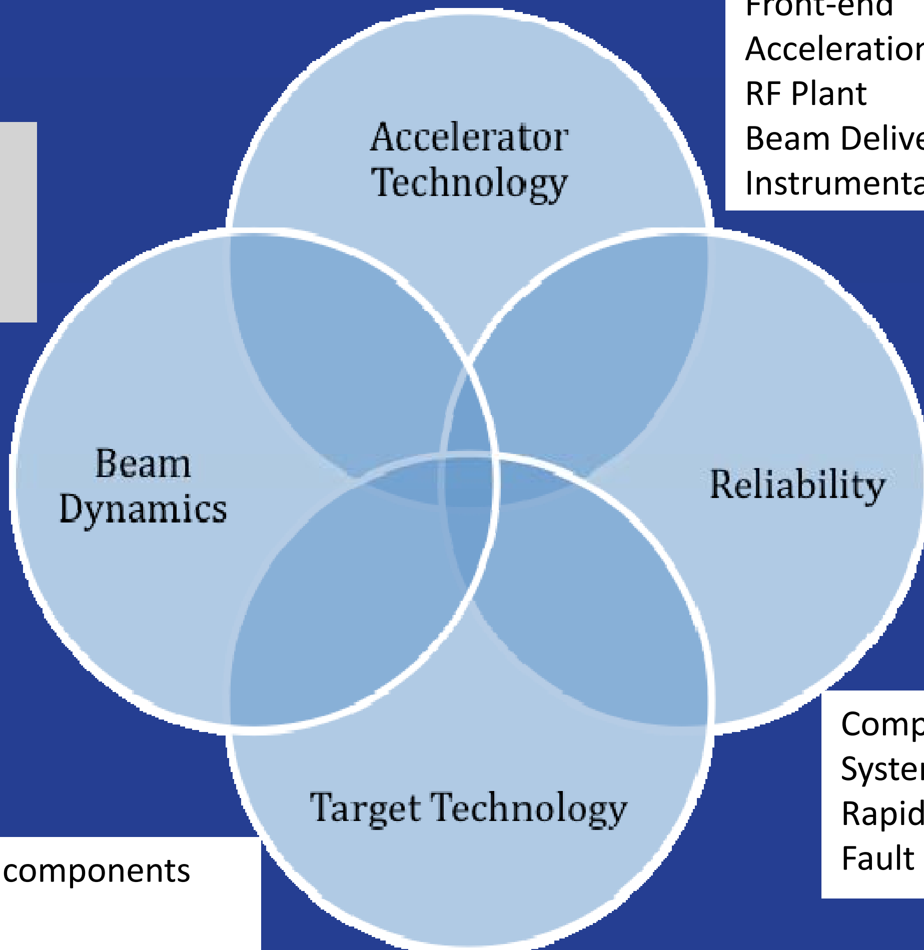
Finding #13

With appropriate scaling at each step along a technology demonstration path, there are no obstacles foreseen that would preclude the deployment of spallation targets at a power level (10 to 30 MW) needed to meet the application of ADS at an industrial scale.

Key technologies and issues for the Accelerator-Target system. Many of the most challenging technical issues are inter-related.

Front-end
Acceleration Section
RF Plant
Beam Delivery System
Instrumentation and Controls

Beam Quality
Beam Loss Mechanisms
Fault Tolerant Design
Beam-Target Interface



Component-level Reliability
System-level Reliability
Rapid-fault recovery
Fault tolerance

Liquid-metal target components
Chemistry Control
Remote Handling
Windowless Design

ADS Technology Readiness Assessment

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	Green	Green	Green
	Reliability	Yellow	Yellow	Red
Accelerating System	RF Structure Development and Performance	Green	Green	Green
	Linac Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
RF Plant	Performance	Green	Green	Green
	Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Red
Beam Delivery	Performance	Green	Green	Green
Target Systems	Performance	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
Instrumentation and Control	Performance	Green	Yellow	Yellow
Beam Dynamics	Emittance/halo growth/beamloss	Green	Yellow	Yellow
	Lattice design	Green	Yellow	Yellow
Reliability	Rapid SCL Fault Recovery	Yellow	Red	Red
	System Reliability Engineering Analysis	Yellow	Red	Red

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.

Finding #14

Technology is sufficiently well developed to meet the requirements of an ADS demonstration facility; some development is required for demonstrating and increasing overall system reliability.

Finding #15

For *Industrial-Scale Transmutation* requiring tens of MW of beam power many of the key technologies have been demonstrated, including front-end systems and accelerating systems, but demonstration of other components, improved beam quality and halo control, and demonstration of highly-reliable sub-systems is required.

Finally

- What's next?

- I would like to thank the Working Group Members for their hard work in producing what I hope is a useful document